The Mars Technology Program

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Abstract

Future Mars missions require new capabilities that currently are not available. The Mars Technology Program (MTP) is an integral part of the Mars Exploration Program (MEP). Its sole purpose is to assure that required technologies are developed in time to enable the baselined and future missions.

The MTP is a NASA-wide technology development program managed by JPL. It is divided into a Focused Program and a Base Program. The Focused Program is tightly tied to the proposed Mars Program mission milestones. It involves time-critical deliverables that must be developed in time for infusion into the proposed Mars 2005, and, 2009 missions. In addition a technology demonstration mission by AFRL will test a LIDAR as part of a joint NASA/AFRL experiment. This program bridges the gap between technology and projects by vertically integrating the technology work with pre-project development in a project-like environment with critical dates for technology infusion. A Base Technology Program attacks higher risk/higher payoff technologies not in the critical path of missions.

1. Introduction

The NASA Mars Exploration Program has plans to implement a series of ambitious missions with launches every two years, to explore Mars. The strategy is referred to "follow the water." There are four exploration objectives that form the basic elements of this strategy: These are: *Life* (understand the potential for life elsewhere in the universe), *Climate* (understand the relationship to Earth's climate change process), *Geology* (understand the solid planet), and *Prepare for Human Exploration* (develop the technology and engineering necessary for eventual human exploration.) Although the current mission queue specified for the first decade does not include a Mars Sample Return (MSR) mission, the likelihood of an MSR mission in the second decade is high. Launches will include landers, orbiters, and MSRs. Currently, NASA and JPL are working to develop a flexible exploration strategy that can respond to discoveries to better align the missions with new science objectives.

A series of Scout missions have been proposed for launch on 4-year centers starting in 2007. The science community would compete for these missions. It is possible that they might involve airborne vehicles, balloons or networks of small landers, but the strongest proposals will be funded regardless of the approach. The first Scout mission competition started in FY '02. NASA will select a set of winning proposals in the fourth quarter of 2002. A down select later will elect one proposal to develop a mission for 2007.

The 2003 Mars Exploration Rovers (MER) mission includes two rovers that are far more capable than the Pathfinder rover. These rovers are planned to be launched in May and June of 2003. The Mars Reconnaissance Orbiter (MRO) with the superior capability of high-resolution imaging will be launched in 2005. The proposed 2009 Mars Science Laboratory (MSL) mission would introduce a number of significant technological innovations.[1] The most important of these are: 1- the ability to make a safe landing at any locality on Mars and 2- the ability to operate an analytical science laboratory on the surface of Mars. These technology innovations would be carried forward into future missions in the second decade, which may include life detection experiments.

The enabling technologies for the proposed 2005 and 2009 missions will be addressed in a *Focused Technology Program* that is tightly tied to the proposed Mars Program mission milestones. It involves time-critical deliverables that must be developed in time for infusion into the proposed Mars 2005 and Mars 2009 missions. This program bridges the gap between technology and projects by vertically integrating the technology work with pre-project development in a project-like environment. The technology work includes validation and risk reduction through simulation, laboratory and field tests and the use of flight experiments when required.

In addition, a *Base Technology Program* will address enhancing technologies for missions proposed for 2009 and beyond. The Base Program stresses breakthrough technology elements that are not in critical path of missions. It will address technology needs that are less mature and higher risk (and higher payoff) than those constituting the Focused Program.

The Focused Technology Program and the Base Technology constitute the elements of the Mars Technology Program (MTP) that is managed by JPL, but which is carried out by the full NASA community.

2. Focused Technology Program

Three critical technology products that are needed for the MSL mission are being developed under missions that will be launched prior to the MSL mission. The objective is to validate these technologies before they are used on the MSL mission. Since the MSL mission includes additional new technology elements, this arrangement will reduce the risk by flight validating some of the technologies prior to the mission.

2.1 AFRL XSS-11

One of the technology products is a Laser Mapper (LAMP). This is a dual purpose instrument. It has the capability of detecting small rocks (~30cm) from 1000 meters which then can be used to maneuver the spacecraft as it is landing to a safer site. LAMP also will provide the capability to track (direction and range) a small (~20 cm diameter) Orbiting Sample (OS) in the Mars orbit in the range of 0.5 to 5000 meters.

This Instrument is currently planned to fly on an AFRL technology experiment minispacecraft called XSS-11. It is planned to be launched on a Minotaur carrier in 2004 or possibly 2005. Figure 1 shows a Concept Development Unit (CDU) that was completed July 2002 and currently is undergoing performance tests. The flight unit is planned to be delivered to AFRL in October of 2003.

The experiment includes releasing a model of an OS from XSS-11 and then performing many maneuvers demonstrating terminal rendezvous capabilities. This experiment will not demonstrate the final phase which is capture. The rendezvous algorithms and software are provided by a NASA New Millennium task called Autonomous Rendezvous (ARX).

Figure 1. Laser Mapper (LAMP)

2.2 Mars Reconnaissance Orbiter (MRO, 2005)

Two technology products are planned to be launched on this mission.

2.2.1 Electra Radio

NASA Mars missions intended for surface operations are data intensive and promise to become vastly more so in the next few opportunities. What were once adequate data return have become inadequate in this day of ever-increasing science data volumes. To meet the expected near and far term Mars Network data and navigation requirements, the Mars Telecom Proximity Payload (MTPP) development is being undertaken, referred to as the

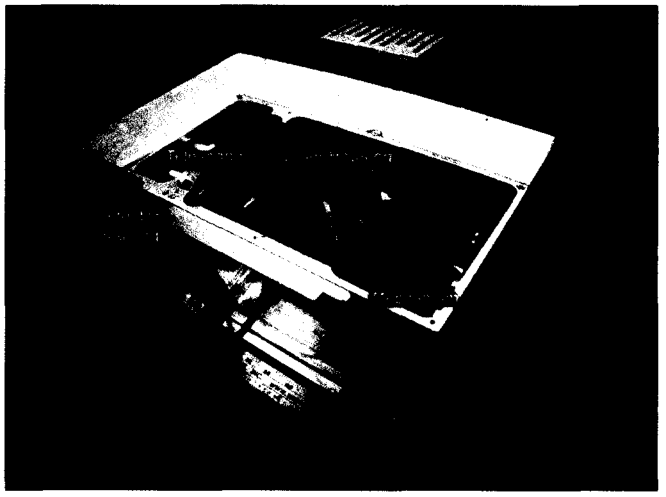

Figure 1. LAMP Concept Development Unit

Electra radio. The current thrust of this development allows it to not only serve the near- and far-term Mars Network needs, but positions it to provide a possible new solution to the direct-to-Earth communications needs of a large class of deep space missions.

The MTPP development will result in a highly capable software based transceiver that can be reprogrammed at any time, pre- or post-launch, to accept new modulation formats, new data structures, new coding algorithms, new carrier frequencies , new data rates, new receiver bandwidths, etc, as the network is refined over multiple Mars opportunities. The overall approach that will be taken is to develop the software reconfigurable transceiver through a combination of modular RF hardware, reconfigurable rad-tolerant FPGA's, rad-hard ASICs, and rad-hard/rad-tolerant microprocessor's. The approach will also be modular in that portions of the transceiver may be utilized for surface assets that do not require full MTPP functionality.

2.2.2 Optical Navigation Camera

The technology is the development of a small, low mass, low power, low volume visible light CCD camera whose prime purpose is high accuracy optical navigation on approach to Mars to enable precision landing for sample return missions. The camera also has application to many other planetary mission navigation situations. In the past, optical navigation has been done with science cameras, which were not optimized for navigation. Those science cameras were much larger than the camera being developed in this task with, for example, apertures of 20 cm and focal lengths of 1.5 to 2 meters, compared to the 6 cm aperture of the opnav camera and the focal length of 0.5 m (folded to about 0.2 m). The mass of about 2.5 to 3 kg of the opnav camera will be much smaller the tens of kg of the Viking, Voyager, Galileo and Cassini cameras. In addition the opnav camera will minimize power to the level of about 2 watts using a hybrid imaging technology (HIT) approach to the standard CCD. The camera must also be designed to be geometrically and thermally stable to 0.1 pixel or better. The camera will be used on approach to Mars to image the satellites of Mars against a star background with 0.1 or better accuracy. Delivery accuracy of the spacecraft will be about 0.5 km. The TRL at the beginning of development was 3, before launch on MRO it will be 7 and after MRO, the camera will be at TRL 9 for future missions. Figure 2 shows a CAD drawing of this camera.

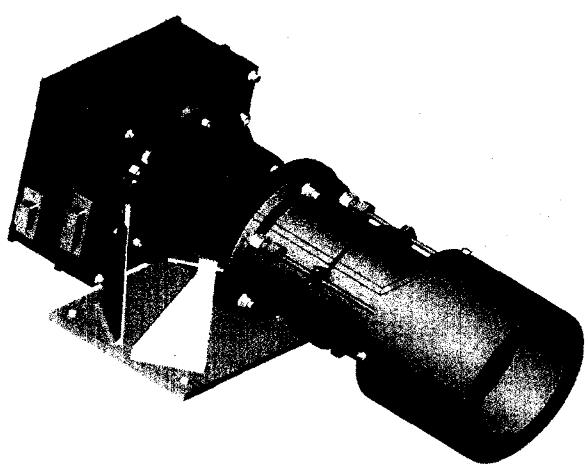

Figure 2. Optical navigation Camera

2.3 Mars Science Laboratory (MSL, 2009)

This mission's main objective is to perform in-situ experiments on the surface of Mars. Sojourner was able to demonstrate rover technology on the surface of Mars and performed minimal science. MER is a more capable rover and will perform remote as well as contact science. MSL is the first mission which will have a onboard laboratory and will perform in-situ analytical experiments.

In addition to being a full science mission, MSL will also provide technology forward to the future missions requiring landing large payloads on the surface of Mars such as a Mars Sample Return mission.

The MSL mission is also defined to be a long-lived mission. This may be accomplished via solar energy or radio isotope powered generators.

From technology point of view, there are two main technology areas that are required to be developed for this mission. One is the Entry, Descent, and Landing (EDL) capability and the second is Surface System. Surface system technology includes rover technology, survivability, and onboard sample preparation and distribution system. In the following we will describe these technology developments.

2.3.1 Entry, Descent and Landing (EDL)

One of the main goals is to develop the capability to land safely near any chosen site (including higher elevations) in order to provide a global access to Mars. To achieve this ability to land safely at any locality on Mars, the entire process of entry, descent and landing was reviewed and innovations are planned to provide the needed capabilities.

The present state of the art for EDL on Mars utilizes radio-based approach navigation, no control of the lift vector during entry, a single stage parachute, and hazard tolerance only to the extent that either airbags or landing struts are utilized. There is no hazard detection/avoidance capability. Variants of this approach were used on Viking and Pathfinder and will be used on the Mars 2003 mission. The errors in approach navigation propagate through the trajectory, resulting in a landing error ellipse ranging from 100 km cross range to 300 km along the downrange vector. The payload mass that can be delivered using existing or anticipated launch vehicles with this system is limited to ~ 70 kg.

Precision landing reduces the risk of encountering hazardous areas such as large craters and steep canyons at any given region of Mars where it is desired to land.

Our goal is to develop new technology to reduce the landing error ellipse to smaller than 3 x 10 km. In addition the payload mass will be raised to ~ 300 kg. To achieve this goal, each step of the EDL process is upgraded with new technology. Figure 3 illustrates the steps involved in precision EDL. Each step is being developed with advanced technology, with systems integration used to assure that all the pieces fit together.

To achieve this goal, three complementary technologies are being developed:

- Precision landing
- Hazard avoidance
- Robust landing

2.3.1.1 Precision Landing

A new optical navigation camera is being developed to use the Martian moons Phobos and Deimos as reference targets for precise entry. A lifting entry vehicle is being developed with L/D ~ 0.25 that is capable of actively guiding itself from entry to parachute deployment despite uncertainties in the entry conditions, atmospheric density profile, winds and aerodynamic performance (Figure 4). A two-stage parachute system will be developed with the subsonic parachute having the potential for para-guidance. Improved descent propulsion will be achieved by recapturing Viking technology with new miniaturized components.

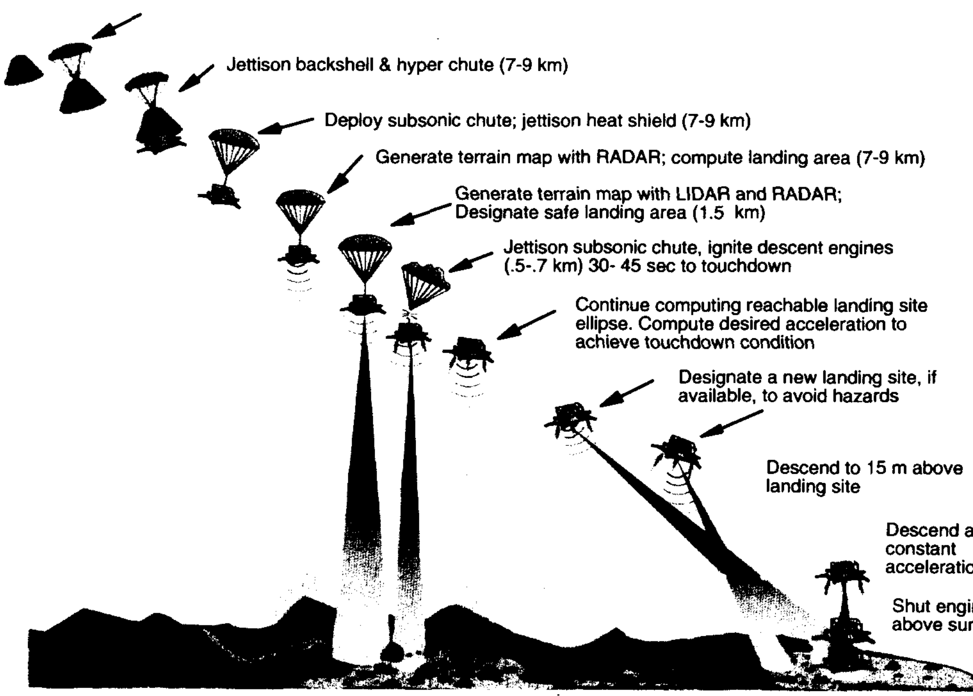

Figure 3. EDL Sequence

2.3.1.2 Hazard Detection and Avoidance

Hazard avoidance provides an "eyes wide open" capability at landing. The overall process is illustrated in Figure 3. This makes it possible to make last-minute adjustments to landing location to avoid large craters, large rocks and steep local slopes. (Figure 5)

The MTP will develop an integrated terminal guidance, navigation and control system that predicts the descent flight path after the subsonic parachute is deployed, detects hazards such as rocks and slopes using active sensors, and after jettisoning the parachute, steers the lander to a safe landing area. A RADAR sensing system for 0-7 km altitudes will be developed to generate initial terrain maps and create initial estimates of the landing area at ~ 7 km altitude. When the capsule descends to ~ 1.5 km, LIDAR is used to augment the RADAR terrain maps, and alternate landing sites are designated if hazards are detected. Field tests will be conducted with rocket sled and helicopter test platforms to validate these technologies. In addition to the LIDAR (or LAMP

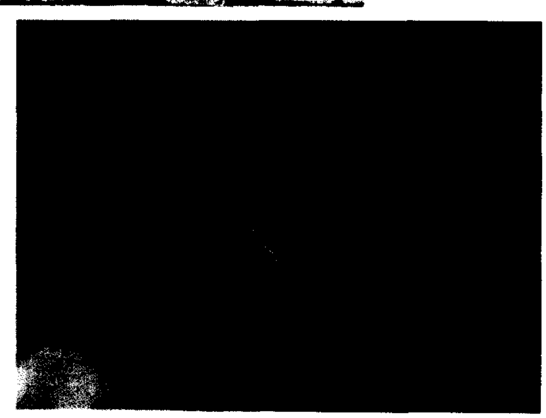

Figure 4. Guided Entry

described earlier) we are also developing Phased Array Radar (PAR). PAR can be activated earlier in the sequence of EDL and therefore may provide more time for the lander to be laterally maneuvered to avoid undesirable landing sites. PAR also is more robust to landing during wind storms that will interfere with LAMP's operation. One of the weaknesses of PAR is that it is not a high resolution sensor, and therefore may not help to avoid 30 to 50 centimeter rocks. The current strategy is to develop both of these sensors and decide later which (or both) will be used in the mission.

2.3.1.3 Robust Landing

Once landing is committed to, this technology makes it possible to tolerate the unexpected or provide resilience to failures in either precision landing or hazard avoidance systems. Two approaches were considered in FY 01 and prototype systems were developed and tested. A peer review of these two systems resulted in selecting the pallet system for further development. (Figure 6)

2.3.2 Surface System Technologies

These include all the technologies that enable a rover to travel long distances, place instruments autonomously, and analyze samples on its onboard laboratory. The rover and its instrumentation must last at least 500 sols.

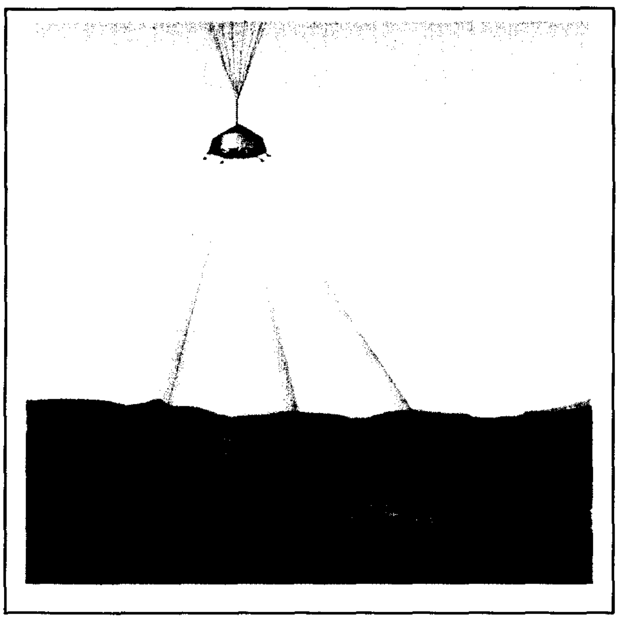

Figure 5. Hazard detection and avoidance

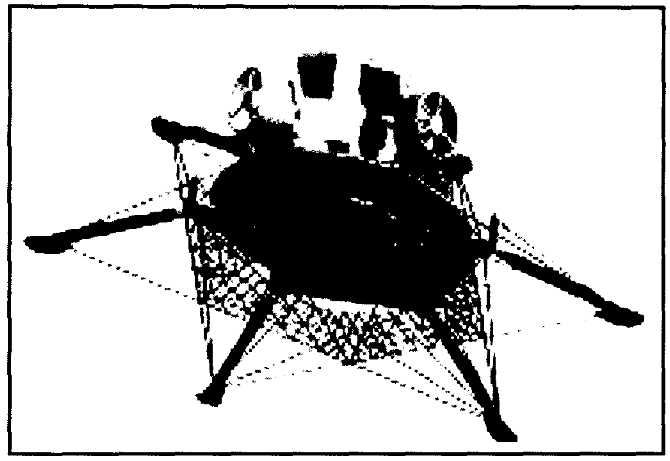

Figure 6. Pallet Landing System

2.3.2.1 Rover Technology

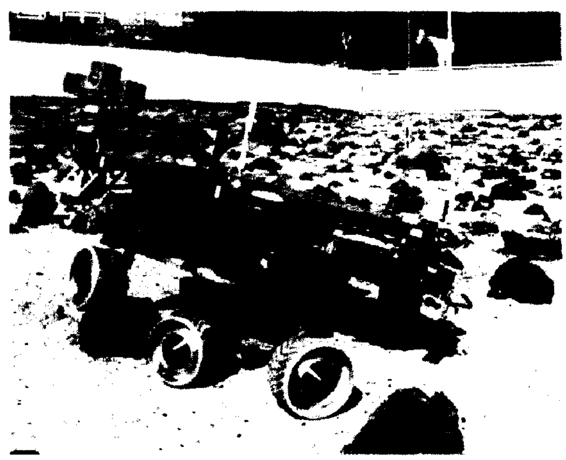

Figure 7. Prototype Mars Rover

Improved rover autonomy is being developed to enable safe navigation as well as autonomous science operations for Mars surface missions. The strategy is to integrate technologies from the Base Program that are competitively selected and integrate them to demonstrate the capabilities that are required for MSL. The Base Program is developing technology for the on-board capability to negotiate relatively long distances (~300 m/sol) without supervision from the Earth during traverses from one exploration site to another. The time delay inherent to Earth-Mars communications makes it impractical to carry out long traverses with Earth supervision. Technology is also under development to reduce the number of uplinks and downlinks required in making scientific observations. New instrument concepts will be integrated with rover platforms. These technologies will be fully tested and validated with full-scale remote terrestrial field trials in simulated Mars terrain, including simulated science operations. Comprehensive control architecture is being developed for autonomous rovers that capture the state of the art in robotics and autonomy software. This system is distinguished by its layered structure using object-oriented hierarchies.

2.3.2.2 Long Life

A study was conducted to determine which of the rover components are likely to fail during the 500 sol mission. This study revealed that there are major weaknesses in the area of mechanical systems, particularly motors and bearings. Another major area was the electronics which would be exposed to Martian temperature and its fluctuation. Research is being conducted to test potential hardware under realistic conditions and improve them.

2.3.2.3 Sample Processing and Distribution

One of the main differences between MSL and MER mission is MSL's capability to analyze Martian samples onboard its analytical laboratory. The laboratory consists of science instruments, sample acquisition, processing, and distribution system.

The science instrument development program is described later in the base program. The sample acquisition may be accomplished by a mini coring device, which has already been developed for NASA and is currently available or by an arm/scoop. This technology exists, because it was developed for the failed Mars Polar Lander (MPL). A Sample Processing and Distribution (SPAD) system is not currently available and research is being funded to develop this capability. The objective is to develop a small system that can crush rocks (0.1-1 mm) and distribute them to various onboard science instruments. Cross contamination for this type of a system is a major concern. A technology requirement has been established to insure that no more than 55 contamination results from one sample to the next. This number can be decreased by processing the second sample more than once, thus reducing the contamination to levels below 5%.

We now elaborate on MSR technologies. Considerable amount of work was done in this area in FY 01, but since the planned MSR mission was delayed, no focus technology exists in MTP. Base technology is however planned that will attempt to perform research on the elements that will help reduce technical risk and will increase the reliability of technology and mission development cost numbers.

2.4 Mars Sample Return

Although, the ultimate architecture of the Mars Sample Return mission is still not settled, the pivotal capabilities that must be developed to enable any Mars Sample Return mission are understood. These capabilities include those developed for the Mars Science Laboratory, as well as technology specific to sample return. The Mars Technology Program will develop needed technology for a future Mars Sample Return mission, and where aspects of the mission remain undecided, will provide technical data and analysis to assist the Mars Program Systems Engineering Team (MPSET) to make these decisions. Sample return technology is divided into the following five elements.

2.4.1 Forward Planetary Protection

Forward planetary protection will protect against transporting Earth-organisms to Mars that could (1) contaminate the planet, or (2) which could appear in returned samples from Mars, or (3) which could interfere with in situ instruments attempting to detect life on Mars. Technology will be developed to produce a robust cleaning method. This will be accompanied by a rapid method for bio-burden validation. It is hoped to use a H_2O_2 plasma sterilization scheme to kill extreme microbes on hardware surfaces. Cleaning and sterilization methods will be validated by tests on hardware subassemblies.

2.4.2 Mars Ascent Vehicle (MAV)

The Mars Ascent Vehicle must transfer clean samples from the surface of Mars to an Earth Return Vehicle located either Mars orbit or on an Earth-bound trajectory. The various alternatives for a MAV rocket approach have been studied by three independent contractors and a technology roadmap has been developed. Reference 3 provides a detailed description of the results from these contractors. This study was lead by a team from NASA Marshall with collaboration from JPL. Figure 9 shows an artist rendition of the MAV launch from the surface of Mars.

2.4.3 Rendezvous and Sample Capture

An *autonomous* sample rendezvous and capture system must be developed with the ability to autonomously locate, track and capture a small sample canister in Mars orbit or deep space for return to Earth. The LIDAR sensor described earlier in this paper is under development for utilization in the autonomous sample rendezvous and capture system.

2.3.4 Sample Containment & Earth Return

In order to carry out a sample return mission, technology must be developed to provide secure containment of the sample, while preventing any possible Mars organisms from being inadvertently released into the Earth's environment. In order to accomplish this, the chain of contact from Mars to Earth must first be broken without breaking the seal on the container. Two complementary techniques for sterilizing exposed sealing plane edges in the airlock break-the-chain concept are must be evaluated. One uses fluorine gas to sterilize the exposed Martian surfaces. The other uses explosive welding to sterilize and seal the exposed surfaces. Further work will bring the fluorine technology to NASA Technology readiness Level (TRL) 6. In addition to breaking the chain of contact, other technologies such as micrometeorite protection and containerization integrity must be developed.

Figure 8. MAV launch

2.4.5 Returned Sample Handling

After the samples are returned to Earth, they must be secured to prevent inadvertent release of possible Mars organisms, and the samples must be protected from contamination by Earth organisms. Returned sample handling technology includes cleaning and sterilization processes, cold sample storage and processing, and life-detection technology.

2.5 Mission Infusion Schedule

The schedule for development of Mars focused technology is primarily driven by the project schedules. The two key dates for technology infusion into the projects are the Preliminary Mission Systems Review (PMSR) and the Preliminary Design Review (PDR).

The maturity of a technology is assessed using the NASA Technology Readiness Level (TRL) scale. Technologies at NASA TRL 5-6 at PMSR will influence the mission concept, and technologies at TRL ≥6 at the time of PDR are candidates for infusion into the baseline project design..

3. Base Technology Program

As described earlier, Base Technology will develop enhancing technologies for baselined missions and future missions, as well as new, enabling technologies for future missions. The goal is to engage the community comprising NASA centers, industry, universities, other government agencies, and JPL to develop Mars exploration technologies based on a competition process (i.e., NRAs). These technologies when appropriate are then integrated into testbeds at JPL and elsewhere to demonstrate technology readiness levels.

3.1 Regional Mobility and Subsurface Access

This area includes innovations in autonomous surface vehicles (rovers), aerial platforms such as balloons and airplanes, subsurface access with drills and other robotic devices, and science operations.

Rover technology will focus primarily on rover autonomy. Enhancing autonomy component technologies will be developed and integrated into newly developed software architecture named CLARAty (short for Coupled Layered Architecture for Robotic Autonomy).

CLARAty is a modular reusable software architecture that is designed to run on a variety of hardware (different rovers, operating systems, and computing hardware). CLARAty has been developed by JPL, CMU, and ARC and has been designated as the software architecture for Mars Technology Program's autonomy software development (Ref 2). The infusion to MSL will be accomplished by early definition of software interfaces and infusion methodology, and parallel development and infusion of software prior to the completion of technology development to TRL 6.

Secondary emphasis will be on novel mechanical mobility systems providing access to difficult-to-reach terrains.

Aerial Vehicles potentially can yield high payoff by providing lightweight aerial platforms such as balloons and aircraft for Scout missions. Technologies are required for deploying and inflating super-pressure balloons, and aircraft designs capable of flight in the tenuous Mars atmosphere, which has the density of the Earth's atmosphere at around 35 km altitude. These platforms would provide access to Mars that is intermediate in scale between orbiters, which can view large areas with relatively low resolution, and rovers, that can examine relatively smaller areas with high resolution. Gliders and balloons would be able to examine intermediate sized areas (hundreds of km) with resolution intermediate between orbiters and rovers.

Subsurface Access element will develop the capabilities for autonomous access to the subsurface of Mars via drilling or moles within limited power and mass allocations. The initial goal is to achieve depths of 1-10 m; the intermediate goal is 200-400 m; and the long-term goal is to achieve depths of up to 2 km.

3.2 Mars Instrument Development Program (MIDP)

The Mars Instrument Development Program (MIDP) provides funds via competitive opportunity to advance the maturity of unique in-situ and remote sensing instruments to characterize the geology and environment of Mars, as well as for life detection (past or present). Technologies will be developed both for mid-TRL (4-6) and low-TRL (1-3) instruments.

3.3 Telecom and Navigation

Telecom and navigation technology investments are focused on Mars-specific needs related to proximity link relay communications and in-situ, radio-based navigation scenarios. Relay communications technologies are aimed at significantly increasing science data return from a wide range of future exploration assets (e.g., landers, rovers, aerobots, microprobes) while minimizing mass, volume, and energy needs. Next-generation network protocols will ensure interoperability while enabling efficient operations. Extraction of radiometric information from these proximity links will also support precision in-situ navigation for scenarios such as approach, surface mobility, and on-orbit rendezvous.

3.4 Advanced Entry, Descent and Landing

Advanced entry, descent, and landing (EDL) is the logical extension of the EDL development in the Focused Technology Program, and it aims to develop an advanced entry, descent, and landing system that provides "pinpoint" delivery (10-100 m accuracy), much more capable hazard avoidance, and a higher payload delivery mass. This element also will develop technologies that enable delivery of smaller payloads to the surface of Mars by addressing the special needs of such missions.

3.5 Planetary Protection

These include innovative technologies intended to satisfy planetary protection requirements for surface, subsurface and atmospheric missions as well as those technologies that allow sample acquisition for in-situ life detection and sample return when the spacecraft has not been cleaned to Planetary Protection IV B level.

3.6 Low-Cost Mission Technologies

These include technologies that will enable post-'09 missions such as the Scout missions. The approach is to identify those technologies that have been identified by the community for low-cost missions, but are not yet developed to TRL 6.

4. Conclusions

The Mars Technology Program is divided into a Focused Program and a Base Program. The Focused Program is tightly tied to Mars Program mission milestones. It involves time-critical deliverables that must be developed in time for infusion into the Mars 2005 and Mars 2009 missions. This program transcends the usual gulf between technology and projects by vertically integrating the technology work with pre-project development in a project-like environment with critical dates for technology infusion. It will primarily address developing technology to enable safe landing anywhere on Mars, long life, rover autonomy, and enabling sample return technologies in the future.

In addition, a Mars Base Technology Program attacks higher risk/higher payoff technologies not in the critical path of missions. The Base Program will also support technologies that may be enabling for Scout missions.

5. Acknowledgement

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